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Experimental Review on Lepton Universality and Lepton Flavour Violation tests at the B-factories

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Since 1999, the B-factories collaborations *BABAR* and Belle have accumulated and studied large samples of tau lepton pairs. The experimental results on Lepton Universality checks and Lepton Flavour Violation searches are reported.

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1. Introduction

In recent years, the *BABAR* and Belle experiments have contributed results on tau lepton physics, which improved the experimental picture of lepton universality and of lepton flavor violation searches.

Both experiments rely on "B-factories" operating at a centre-of-mass energy of 10.58 GeV on the $\Upsilon(4s)$ peak, just above the threshold for producing B-mesons. *BABAR* operates at the PEP-II complex at SLAC, which collides 9 GeV electrons against 3.1 GeV positrons, and has recorded about $420\,\mathrm{fb}^{-1}$ of data by May 2007. Belle operates at the KEKB B-factory in Japan, which collides 8 GeV electrons against 3.5 GeV positrons, and has recorded about $710\,\mathrm{fb}^{-1}$ of data by May 2007.

The *BABAR* [1] and Belle [2] detectors share several similarities and both include a silicon microvertex detector, a drift chamber, a 1.5 T solenoidal superconducting magnet, an electromagnetic calorimeter based on Cesium Iodide crystals, and a segmented muon detector in the magnet return yoke. The two experiments differ in the particle identification strategy: Belle uses an aerogel threshold Cherenkov detector together with time-of-flight and tracker dE/dx, whereas *BABAR* relies on a ring-imaging Cerenkov detector supplemented by the dE/dx in the trackers.

With a total now exceeding $1.1\,\mathrm{ab}^{-1}$ of integrated luminosity and a $e^+e^- \to \tau^+\tau^-$ cross-section at 10.58 GeV of 0.919 nb [3], B-factories recorded in excess of 10^9 tau pairs, which allow for improving statistics-limited results, like in particular searches for tau lepton flavor violating decays.

2. Lepton universality tests

The Standard Model (SM) predicts that all lepton doublets have identical couplings to the W boson. Ratios of measured decay widths of leptonic or semileptonic decays which only differ in the lepton flavour test whether the W interaction is universal for the three lepton flavours. The present data are consistent with the universality of the leptonic charged-current couplings to the 0.2% level [4]. B-factories have produced results on the tau mass, the tau lifetime, and could in principle measure tau branching fractions that improve the experimental knowledge on the less precisely known factors in the following expressions for leptonic coupling ratios, which the SM predicts to be consistent with unity:

$$\frac{\Gamma_{\tau\to e}}{\Gamma_{\mu\to e}} \propto \left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\mathscr{B}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{f(m_e^2/m_\mu^2)r_{EW}^\mu}{f(m_e^2/m_\tau^2)r_{EW}^\tau} \tag{2.1}$$

$$\frac{\Gamma_{\tau\to\mu}}{\Gamma_{\mu\to e}} \propto \left(\frac{g_\tau}{g_e}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\mathscr{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{f(m_e^2/m_\mu^2)r_{EW}^\mu}{f(m_\mu^2/m_\tau^2)r_{EW}^\tau} \tag{2.2}$$

$$\frac{\Gamma_{\tau\to e}}{\Gamma_{\tau\to\mu}} \propto \left(\frac{g_e}{g_\mu}\right)^2 = \frac{\mathscr{B}(\tau^- \to e^-\bar{\nu}_\mu\nu_\tau)}{\mathscr{B}(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau)}\frac{f(m_\mu^2/m_\tau^2)}{f(m_e^2/m_\tau^2)} \tag{2.3}$$

In the above expressions, Γ represents partial widths, τ_ℓ lepton lifetimes, m_ℓ lepton masses, $\mathscr{B}$ branching fractions; $f(x) = 1-8x+8x^3-x^4-12x\ln x$ are phase space factors [5], $r_{EW}^\ell \approx 1$ correspond to electro-weak radiative corrections [5].

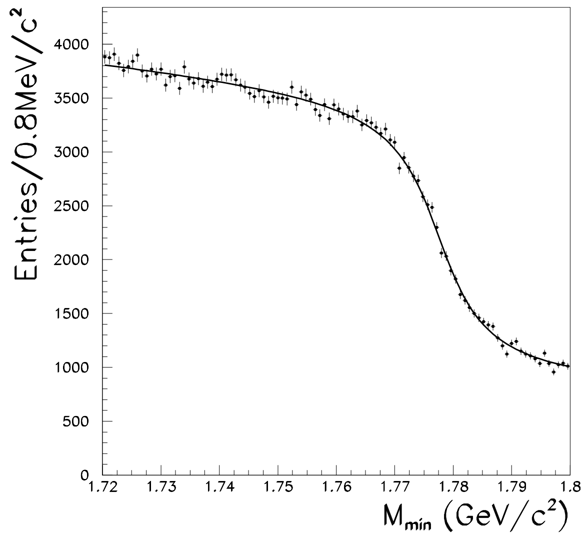

Figure 1: Pseudomass distribution for M_{min} for the $\tau \to 3\pi\nu$ candidates. The tau mass is a parameter of the fit shown with a solid line.

2.1 Tau mass

The mass of the tau lepton appears at the fifth power in the coupling ratio expressions 2.1 and 2.2, contributing a relative uncertainty of 0.08% [6].

BELLE measured the tau mass using a pseudomass technique that was first employed by the ARGUS collaboration [7]. Tau pairs candidates are selected where one tau decays into a single prong (electron or muon), and the other one decays into 3-prongs, all of which are pions, with no additional π^0. Then a quantity M_{min} is computed:

$$M_{\mathrm{min}} = \sqrt{M_X^2 + 2(E_{\mathrm{beam}} - E_X)(E_X - P_X)}, \tag{2.4}$$

which is less than or equal to the tau lepton mass. M_X, E_X and P_X are the invariant mass, energy and absolute value of the momentum, respectively, of the hadronic system in the center-of-mass (c.m.) frame, and E_{beam} is the energy of the electron (or positron) in this frame. The distribution of M_{min} extends up to and has a sharp edge at M_τ, smeared by detector resolution and initial and final state radiation. The edge position obtained from a fit to the M_{min} distribution is relatively insensitive to the background and is a precise estimator of the tau mass. The offset between the edge and the tau mass has to be estimated with a Monte Carlo. The measurement (on $414\,\mathrm{fb}^{-1}$ of data) reaches a precision close to the present BES-dominated world average, $m_\tau = 1776.99^{+0.29}_{-0.26}$ [6]:

$$m_\tau = 1776.61 \pm 0.13 \pm 0.35\,\mathrm{MeV} \quad [8]. \tag{2.5}$$

The limiting systematic contributions to this result come from the understanding of the momentum scale and the reliability of the simulation in estimating the offset between the tau mass and the edge position. The uncertainty on the momentum scale is assessed by comparing the reconstructed B meson masses to their world average, which is know up to about $1.5\,\mathrm{MeV}$ [6], and noting that the di-muon invariant mass peak matches the center of mass event energy determined by

the beam energies withing 3 MeV. Apparently, measurement conducted at threshold with machines where the beam energy can be calibrated through resonant depolarization, suffer from smaller systematic uncertainties, as the recent KEDR result shows ($1776.80^{+0.25}_{-0.23} \pm 0.15$ MeV [9]). KEDR aims to obtain a final accuracy of 0.15 MeV, and BESIII aims at a precision better than 0.1 MeV.

2.2 Tau lifetime

The tau lepton lifetime is known up to 0.3% and is the least precisely known factor in the coupling ratio expressions 2.1 and 2.2. *BABAR* has presented a preliminary measurement of the tau lifetime with an error comparable to the present world average:

$$\tau_\tau = 289.4 \pm 0.9 \pm 0.9 \text{ fs} \quad [10]. \tag{2.6}$$

The measurement uses about $80\,\text{fb}^{-1}$ of data and is based on an extremely pure (99.4%) yet scarcely efficient (0.2%) selection of 1 against 3-prong events in the c.m. system, where the 1-prong track is an identified electron. Electron identification is used because it is more efficient and less contaminated with hadrons with respect to muon tagging. The selected tau candidates are about 300,000 and include about 0.2% hadronic background, 0.4% Bhabha background and a negligible amount of two-photon events.

The measurement is based on the reconstruction of the decay length of the tau that decayed into the 3-prong tracks. Using a novel technique aimed at minimizing the systematic dependence on the detector alignment, the tau decay vertex is first computed in a plane transverse with respect to the beam axis. The transverse decay length is computed within the transverse plane by projecting the vector from the luminous region center to the tau decay vertex along 3-prong total momentum direction (which approximates the tau flight direction). The tau decay length is finally reconstructed by projecting the transverse decay length onto the 3-prong total momentum direction.

The mean decay length is determined with an average, abstaining on purpose from weighting events according to their estimated errors in order to minimize systematic effects from alignment and detector material modeling. The mean lifetime is determined using the Monte Carlo prediction of the average tau momentum, using the KKMC generator [12], which includes complete 2nd order radiative corrections. The measurement offset that originates from tracking errors correlations [11] and from approximating the tau momentum direction with that of the 3-prong total momentum is subtracted using the Monte Carlo simulation.

Finally, the contribution of background is subtracted. While hadronic background is simulated, a statistically adequate Monte Carlo simulation of Bhabha events is impractical because the relevant cross-section is about 20 times the tau production cross section (≈ 1 nb), therefore a data control sample is used to estimate both the Bhabha contamination and its decay length distribution.

Systematic uncertainties come mainly from the reliability of the measurement bias subtraction using Monte Carlo, from detector alignment, from the mean tau momentum Monte Carlo simulation, and from background subtraction. This measurement includes a study of the effects of detector misalignment. Decay length shifts with respect to a perfectly aligned detector are measured on simulated Monte Carlo events by refitting tracks from coordinates taken on a detector that is purposefully distorted. Six representative distortions are applied by displacing the silicon vertex detector wafer positions according to the observed distortions and uncertainties that are derived from reconstructed data.

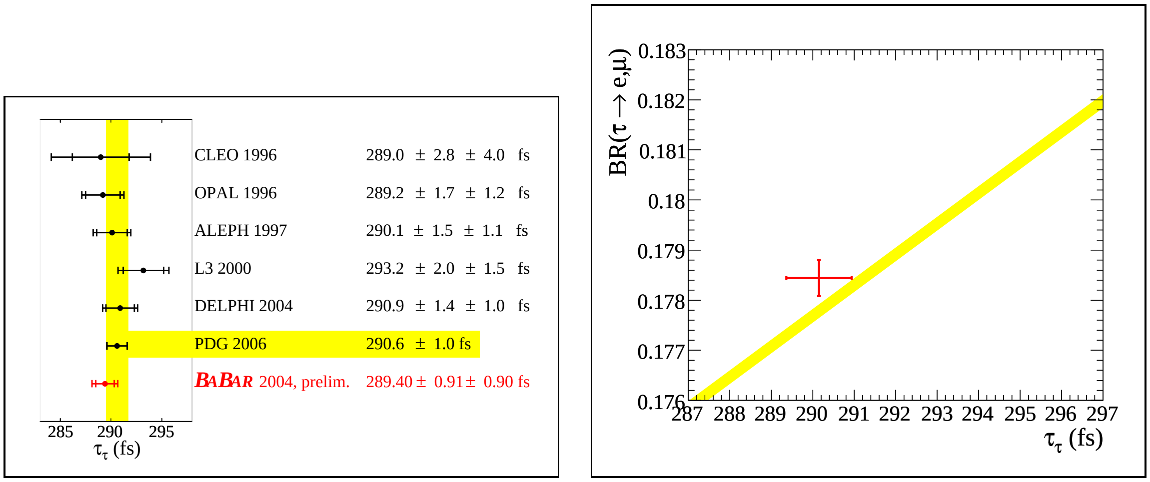

Figure 2: Selected tau lifetime measurements (left) and check of the Standard model (SM) prediction of universal leptonic couplings to the W (right) combining the present tau lifetime world average with the *BABAR* preliminary result. The thickness of the oblique line represents the uncertainty of the SM constraint, and is dominated by the uncertainty on the tau mass.

This preliminary measurement contributes the largest experimental improvement in recent years for the coupling ratio expressions 2.1 and 2.2. Figure 2 reports the measurement compared with the present world average and previous selected measurements [13]. Combining the *BABAR* 2004 result with the present world average assuming no systematic error correlations we obtain

$$\tau_\tau = 290.15 \pm 0.79 \text{ fs.} \tag{2.7}$$

Using the present world averages, we present an updated check of lepton universality in Figure 2 and updated determinations of the coupling ratios

$$\frac{g_\mu}{g_\tau} = 0.9982 \pm 0.0020, \quad \frac{g_e}{g_\tau} = 0.9980 \pm 0.0020, \quad \frac{g_{e,\mu}}{g_\tau} = 0.9981 \pm 0.0017, \tag{2.8}$$

where $g_{e,\mu}$ is determined assuming $g_e = g_\mu$ holds for the theory.

In the recent past, LEP experiments improved considerably the experimental precision on the tau lifetime profiting from ideal conditions in most respects but statistics: there high momentum tracks had small impact parameter errors due to multiple scattering, tau events had a distinctive topology that permitted a pure and efficient selection against backgrounds, vertex detectors provided precise tracking close to the origin and systematic uncertainties from detector misalignment were reduced thanks to the complete and uniform acceptance in the azimuthal angle [11]. B-factories appear to be the only facilities where the tau lifetime measurement can be improved in the near future and they can overcome with statistics the disadvantages related to increased multiple scattering due to lower momenta and to less favourable physics conditions for an efficient and pure selection.

2.3 Tau leptonic branching fractions

B-factories have not yet succeeded in matching LEP experiments regarding the measurement of the tau leptonic branching fractions, because the systematic precision is limited by uncertainties

on the normalization of the number of produced tau leptons, arising from uncertainties on the integrated luminosity corresponding to the analyzed event samples and on the cross-section for tau pair production at the $\Upsilon(4s)$. Uncertainties on luminosity are about 1% to be compared with better than 0.1% for LEP experiments. Until recently, the uncertainty on the tau pair cross-section was estimated by comparing the KoralB [14] and KKMC predictions to be 2.2%. However there has been remarkable progress that led to a new estimate of the tau pair cross section at the $\Upsilon(4s)$:

$$\sigma(e^+e^- \to \tau^+\tau^-) = 0.919 \pm 0.003\,\text{nb} \quad [3]. \tag{2.9}$$

Furthermore, B-factories may measure ratios of branching fractions (see eq. 2.3) whose uncertainties won't be limited by the understanding of luminosity and cross-section, but only by the systematics related to electron versus muon identification and to background suppression and subtraction.

3. Lepton Flavour Violation tests at the B-factories

3.1 Common analysis features

The typical tau LFV decay search at the B-factories selects low track multiplicity events that have 1 against 1 or 3 tracks in the c.m. frame. The thrust axis is used to define two hemispheres, each of which is then examined for consistency with a tau LVF decay, while the other one must be compatible with a known tau decay. Unlike known tau decays, which include at least one neutrino, the reconstructed products of a LFV tau decay are expected to match the tau mass and half the c.m. energy within the experimental resolution. It is worth noting that physics effects also limit the experimental accuracy in reconstructing the parent tau energy and mass from its decay products: initial and final state radiation affect the tau energy itself before decay, and radiation in decay and Bremsstrahlung from the decay products change the reconstructed energy and invariant mass. The energy is reconstructed with a typical resolution of 50 MeV and, when using a total energy constraint to half the c.m. energy, the invariant mass is reconstructed with a resolution of about 10 MeV. Selected events around the expected energy and mass within 2 or 3 standard deviations are then investigated looking for an excess over the expected background.

The amount of expected background is normally estimated using the distribution shapes from the Monte Carlo simulation normalized to the observed events in a two-dimensional sideband region around the signal region on the energy-mass plane. The signal efficiency is estimated with a Monte Carlo simulation and typically lies between 2% and 10% depending on the channel. Typical cumulative efficiency components include 90% for trigger, 70% for geometrical acceptance and reconstruction in the detector, 70% for reconstructing the selected track topology, 50% for particle identification, 50% for additional selection requirements before checking the reconstructed energy and mass, and 50% for requiring consistency with the expected energy and mass. The selection efficiency and background suppression are optimized to give the best "expected upper limit" assuming that the data contain no LFV signal. The optimization and all systematic studies are completed while maintaining the experimenter “blind” to data events in the signal box in the energy-mass plane, in order to avoid experimenter biases.

When the expected background in the signal region is of order one or less, the number of signal events is normally set to the number of observed events minus the background, while in presence

of sizable background the numbers of background and signal events are concurrently determined from a fit to the mass distribution of events that have total energy compatible with the expected one.

3.2 Results

LFV decays can be grouped in the following categories: tau to lepton-photon ($\tau \to \ell\gamma$, where $\ell = e, \mu$), tau to three leptons or one lepton and two charged hadrons ($\tau \to \ell_1\ell_2\ell_3$, $\tau \to \ell h_1 h_2$), tau to a lepton and a neutral hadron ($\tau \to \ell h^0$, where $h^0 = \pi^0, \eta, \eta', K_s^0, etc.$).

Belle has reported preliminary results for $\tau \to \mu\gamma$ and $\tau \to e\gamma$ [15] based on the analysis of $535\,\mathrm{fb}^{-1}$ of data. The $\tau \to \mu\gamma$ ($\tau \to e\gamma$) searches have a 5.1% (3%) signal efficiency within a 2σ elliptical signal region in the energy-mass plane plane. A two-dimensional unbinned extended maximum likelihood fit for signal and background in the signal region obtains $-3.9^{+3.6}_{-3.2}$ ($-0.14^{+2.18}_{-2.45}$) signal and $13.9^{+6.0}_{-4.8}$ ($5.14^{+3.86}_{-2.81}$) background events. Frequentist 90% CL limits are obtained by running Monte Carlo simulations in which the signal is increased until 90% of the fits obtain more than the observed signal events: $\mathscr{B}(\tau \to \mu\gamma) < 0.45 \cdot 10^{-7}$ and $\mathscr{B}(\tau \to e\gamma) < 1.2 \cdot 10^{-7}$.

BABAR has recently submitted for publication [16] and Belle has recently reported [17] improved results on tau to three leptons LFV searches based on enlarged event samples of $400\,\mathrm{fb}^{-1}$ and $535\,\mathrm{fb}^{-1}$ respectively. The two analyses have similar signal efficiencies (5.5%$-$12.5%) although different strategies are adopted to define the signal regions in the energy-mass plane: Belle uses ellipses large enough to contain 90% of signal events, while *BABAR* uses rectangular signal boxes optimized to obtain the lowest expected upper limit in case there is no signal. The Belle selection is significantly more effective in suppressing the background, which is expected to be $0.01-0.07$ events in all channels but the three electron one, where 0.4 events are expected because of Bhabha contamination. The background in the signal region is estimated from the mass distribution sidebands, assuming it is constant, using looser selection criteria to get reasonable samples close to the signal region. No details are given on how the extrapolation is done for the full selection. *BABAR* expects $0.3-1.3$ background events, i.e. of order one, since the selection is optimized for the best expected upper limit, at the risk of getting background events in the signal region. Belle observes no candidate signal events in $535\,\mathrm{fb}^{-1}$ of data in all modes, and calculates upper limits using Feldman and Cousin ordering [17, 18] in the range $[2.0-4.1] \cdot 10^{-8}$, depending on the mode. *BABAR* observes from 0 to 2 events in $376\,\mathrm{fb}^{-1}$ of data, and calculates upper limits according to Cousin and Highland prescription [19] with no Feldman and Cousin ordering in the range $[4-8] \cdot 10^{-8}$.

BABAR has recently published new results on tau LFV decays into a lepton and a hadron pseudoscalar π^0, η, η' [20]. In these analyses both of the $\eta \to \gamma\gamma$ and the $\eta \to 3\pi$ decay modes are used for the analyses, and η' candidates decaying both to $\eta 2\pi$ and $\gamma 2\pi$ are considered. The expected background per channel is between 0.1 and 0.3 events. Summing over all ten modes, 3.1 background events are expected, and 2 events are observed.

Belle has recently reported improved results on tau LFV decays into a lepton and a vector meson V^0 [21], with $V^0 = \phi$, ω, K^{*0} or $\bar{K}^{*0}$, using $543\,\mathrm{fb}^{-1}$ of data. No excess of signal events over the expected background is observed, and upper limits the branching fractions are obtained in the range $(0.7-1.8) \cdot 10^{-7}$ at 90% CL.

Channel	Belle		*BABAR*		combined	
	UL90 (10^{-7})	Lumi (fb^{-1})	UL90 (10^{-7})	Lumi (fb^{-1})	UL90 (10^{-7})	Lumi (fb^{-1})
$\mu\gamma$	0.5^*	535	0.7	232	0.16	767
$e\gamma$	1.2^*	535	1.1	232	0.94	767
$\mu\eta$	0.65^*	401	1.5	339	0.51	740
$\mu\eta'$	1.3^*	401	1.3	339	0.53	740
$e\eta$	0.92^*	401	1.6	339	0.45	740
$e\eta'$	1.6^*	401	2.4	339	0.90	740
$\mu\pi^0$	1.2^*	401	1.5	339	0.58	740
$e\pi^0$	0.8^*	401	1.3	339	0.44	740
$\ell\ell\ell$	$0.20-0.41^*$	535	$0.4-0.8^*$	376		
$\ell hh'$	$2-16$	158	$1-5$	221		
ℓV^0	$0.7-1.8^*$	543				
μK_S	0.49	281				
eK_S	0.56	281				
$\Lambda\pi, \overline{\Lambda}\pi$			$5.8-5.9^*$	237		
$\Lambda K, \overline{\Lambda}K$			$7.2-15^*$	237		
$\sigma_{\ell\tau}/\sigma_{\mu\mu}$			$40-89$	211		

(* preliminary)

Table 1: Summary of 90% CL upper limits on tau LFV decays from the B-factories. An asterisk indicates a preliminary result. h and h' denote a charged pion or kaon. Banerjee's combination of a subset of these channels is also included.

BABAR reported also on less conventional searches of tau LFV decays into $\Lambda\pi$ [26] and of LFV in tau production ($e^+e^- \to \ell\tau$) [27], finding no signal.

The above results and additional B-factories LFV results [22 – 24] are summarized in Table 1. At the Tau2006 conference in Pisa, Swagato Banerjee presented frequentist combinations [25] of some measurements, which are also included in the table.

3.3 Prospects

While Belle plans to run until it will collect $1\,\mathrm{ab}^{-1}$ of data, *BABAR* is funded to run until September 2008, when it expects to reach a total integrated luminosity of about $0.8\,\mathrm{ab}^{-1}$. In case there is no signal, the expected upper limits on the number of selected signal events will improve depending of the amount of irreducible background in each channel:

- when the expected background is large ($N_{\mathrm{BKG}} \gg 1$), the expected upper limit is $N_{90}^{\mathrm{UL}} \approx 1.64\sqrt{N_{\mathrm{BKG}}}$;
- when the expected background is small ($N_{\mathrm{BKG}} \ll 1$), using [19] one gets $N_{90}^{\mathrm{UL}} \approx 2.4$.

Reducing the background below few events does not much improve the expected limit if significant efficiency is lost in the process, therefore optimized searches often enlarge the acceptance until

$N_{\rm BKG} \approx 1$. For the cleaner channels, analyses can be optimized for an increased data sample to keep $N_{\rm BKG} \approx 1$ without loosing a significant part of the signal efficiency: in this best case scenario, the expected upper limits will scale as $N_{\rm BKG}/\mathscr{L}$ i.e. as $1/\mathscr{L}$. On the other hand, if no optimization is possible, just keeping the current analyses will provide upper limits that scale as $\sqrt{N_{\rm BKG}}/\mathscr{L}$, i.e. as $1/\sqrt{\mathscr{L}}$.

Mike Roney has recently estimated [28] that for $\tau \to \ell\gamma$ analyses the background coming from $\tau \to \ell\nu\nu$ decays and initial and final state photons can be considered "irreducible" at its present level (20% of the total). In these conditions, the final combined Belle and *BABAR* data set will allow for expected upper limits in the range $[0.1-0.2] \cdot 10^{-7}$. The actual combined upper limit obtained by Banerjee [25] for $\tau \to \mu\gamma$ is already in that range as a consequence of a downward fluctuation of the observed events with respect to the expected background.

Other tau LFV decay channels ($\tau \to \ell\ell\ell$, $\tau \to \ell hh$, $\tau \to \ell h^0$) do not yet appear to be background limited and their expected expected upper limits with the full B-factories dataset are about $0.1 \cdot 10^{-7}$.

Beyond the current B-factories facilities, there are proposals for super B-factories [29] that would permit a 100 fold increase in the size of the tau pairs sample: this would allow probing tau LFV decays at the 10^{-9}–10^{-10} level.

Acknowledgments

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